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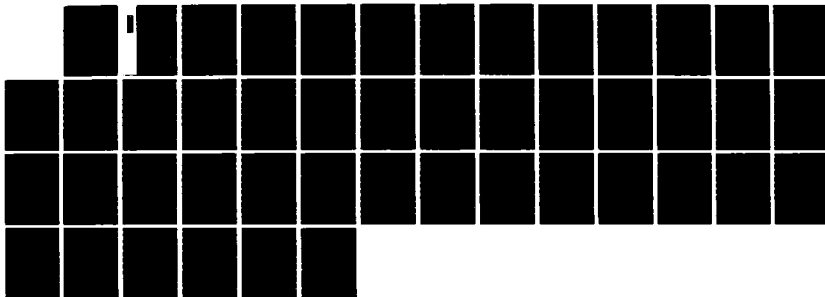
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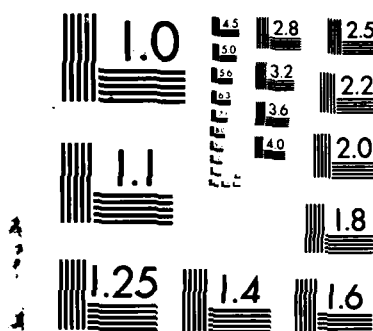
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Report ME-TSPC-TR-85-10
July 1985

Annual Summary Report
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**Research on Aero-Thermodynamic
Distortion Induced Structural
Dynamic Response of Multi-Stage
Compressor Blading**

Sanford Fleeter

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Purdue University
West Lafayette, Indiana 47907

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RESEARCH ON AERO-THERMODYNAMIC DISTORTION
INDUCED STRUCTURAL DYNAMIC RESPONSE OF
MULTI-STAGE COMPRESSOR BLADING

SANFORD FLEETER

July 1985

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Prepared for

Directorate of Aerospace Sciences
Air Force Office of Scientific Research

ABSTRACT

The structural dynamic response of turbomachinery components to aero-thermodynamic distortion induced excitations is an item of major concern in the design of advanced gas turbine engines. The rotor speeds at which these resonant forced responses occur can be predicted with Campbell diagrams. However, due to the inadequacies of existing time-variant aerodynamic models, no accurate prediction can be made for the amplitude of the resulting vibrations and stresses.

The overall objective of this research program is to quantitatively investigate the fundamental phenomena relevant to aero-thermodynamic distortion induced structural dynamic blade responses in multi-stage gas turbine engines. Unique unsteady aerodynamic data are obtained to discriminate the driving phenomena, direct the modeling of these phenomena, and to validate and indicate necessary refinements to state-of-the-art analyses. Also, a first principles capability to predict the vibrational response amplitude of blading due to aerodynamic excitations will be developed. In addition, for the first time, a viscous flow unsteady aerodynamic model appropriate for forced response predictions will be developed.

This report summarizes the progress and results obtained during the period from April 16, 1984 to May 15, 1985. These include: completion of the development and implementation of the steady and unsteady data acquisition and analysis systems; instrumentation of rotors and additional stators with new dynamic pressure transducers which offer increased sensitivity and reduced size; implementation of the cross hot-wire system and the subsequent measurement of the unsteady aerodynamic forcing functions to the stator vanes; continuation of preparations for the rotor experiments including the design and start of fabrication of the signal conditioning to be used in the rotating frame of reference; completion of preparations for the vane row potential interaction experiments; formulation of the viscous flow unsteady aerodynamic model; completion of the initial first stage vane row unsteady aerodynamic experiments; initiation of the multi-stage interaction experiments on the vane rows; analysis of the initial multi-stage vane row unsteady aerodynamic data, resulting in significant implications regarding the validity of the small perturbation modeling concept utilized in forced response unsteady aerodynamic models.



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I. INTRODUCTION

The structural dynamic response of fan, compressor, and turbine blading to aero-thermodynamic distortion induced excitations is a current item of great concern to designers and manufacturers of gas turbine engines for advanced technology applications. Destructive aerodynamic forced responses of gas turbine engine blading have been generated by a wide variety of aero-thermodynamic distortion sources. These include: blade wakes; multi-staging interaction effects; large angle of attack or yaw; engine exhaust recirculation; cross-flow at the inlet; pressure variations on the engine due to external aerodynamics; and armament firing. The following physical phenomena have been identified as being significant with regard to aero-thermodynamic distortion induced structural dynamic responses of fan and compressor blading.

- * Resonance
- * Multi-stage interactions
- * Potential flow field interactions
- * Stall
- * Flow separation

- * Inlet gusts
- * Time-varying inlet flows
- * Turbulence

The first principles prediction of the structural dynamic response associated with all of the above physical phenomena is identical, involving the following elements. Spatially periodic variations in pressure, velocity, temperature, and flow direction of the exit flow field of an upstream element appear as temporally varying in a coordinate system fixed to the downstream row. As a result, individual airfoils are subject to a time-variant aerodynamic forcing function which can induce high level vibratory stresses.

The analysis of the aerodynamically forced response vibratory behavior of a blade or vane row requires a definition of the unsteady forcing function in terms of its harmonics. The time-variant aerodynamic response of the airfoil to each harmonic of this forcing function is then assumed to be comprised of two parts. One is due to the disturbance being swept past the non-responding fixed airfoils. The second arises when the airfoils respond to this disturbance. Mathematically these effects are modeled by two distinct analyses. A linearized small perturbation gust analysis is used to predict the time-variant aerodynamics of the fixed non-responding airfoils to each harmonic of the disturbance. A self-induced unsteady aerodynamic analysis

wherein the airfoils are assumed to be harmonically oscillating is then used to predict the additional aerodynamic effects due to the airfoil response. Superposition of these two effects can be performed only with knowledge of the modal pattern. Thus, a model with key elements consisting of the gust analysis, a self-induced unsteady aerodynamic analysis, and an airfoil structural analysis is necessary.

The unsteady small perturbation gust and self-induced unsteady aerodynamic analyses are two dimensional and, as such, are coupled to the airfoil structural analysis by means of a strip theory approximation. Thus, the airfoil is considered to consist of a series of individual and independent two dimensional aerodynamic regions. The time-variant aerodynamic analyses are then applied to each such individual region, with the characteristic parameters including the Mach number, reduced frequency, stagger angle, and solidity, taken as the average value at the inlet boundary. It should be noted that there is no coupling between adjacent aerodynamic regions. Hence, aerodynamic forced vibrations involving spanwise variations in unsteady aerodynamics cannot be treated, i.e., if spanwise variations exist in the aerodynamic forcing function not caused by simple inlet spanwise variations in the Mach number, reduced frequency, stagger angle, or solidity, such a strip theory design system is of no value. Some of the previously noted forced response sources may fit into this category, as for example, the case of rotor tip vortices generating a forced response in a downstream blade or vane row.

II. PROGRAM OBJECTIVES

The overall objective of this research program is to quantitatively investigate the fundamental phenomena relevant to distortion generated aero-thermodynamic induced structural dynamic effects in multi-stage gas turbine engine blade rows. Unique unsteady aerodynamic data will be obtained on multi-stage stationary and rotating blade rows to discriminate the driving phenomena, direct the modeling of these phenomena, and to validate and indicate necessary refinements to current state-of-the-art analyses. Also, a first principles capability to predict the vibrational response amplitude of blading due to aerodynamic excitations will be developed. In addition, for the first time, a viscous flow unsteady aerodynamic model appropriate for forced response predictions will be developed.

From first principles considerations, the relevant fundamental physical phenomena are identical for the various sources of aero-thermodynamic distortion. Hence, to accomplish this overall objective in a timely and efficient manner, while obtaining results of direct interest and significance to the gas turbine engine community, this research program is concerned with the time-variant aerodynamics and structural dynamic response of multi-stage stationary and rotating blade rows, with the primary source of excitation initially being the wakes from upstream blade elements and blade row potential flow interactions. Thus, the specific objectives of this program include the following.

- * The experimental determination of the fundamental time-variant gust aerodynamics associated with variations in forcing function waveform, incidence angle (loading), reduced frequency, solidity, and multi-stage effects on both stationary and rotating blade rows as well as the investigation of the validity of:
 - * the two-dimensional linearity and superpositioning assumptions;
 - * the small perturbation modeling concept.
- * The development of a first principles capability to predict the vibrational response amplitude of blading.
- * The development of an unsteady aerodynamic analysis which includes viscous effects.

Thus, this program is directed at providing fundamental time-variant aerodynamic data which not only address the validity of the most basic assumptions inherent in these analyses and in the structure of forced response design systems, but also are appropriate to validate and indicate refinements to the current state-of-the-art two-dimensional gust analyses. In addition, first principles predictive aerodynamically forced response models, including viscous effects, will be developed.

III. TECHNICAL APPROACH

The technical approach to achieve the overall program objectives requires that high-quality, detailed aerodynamic data be acquired and analyzed from benchmark experiments which model the fundamental flow physics of aero-thermodynamic induced structural dynamic effects in multi-stage gas turbine engines. These data must also be correlated with appropriate state-of-the-art analyses. In addition, advanced mathematical models and techniques for the prediction of these phenomena must be developed and experimentally verified.

The approach to achieving the experimental objectives is to measure and analyze the steady and time-variant pressure distributions on both stationary and rotating blade rows in controlled experiments which model the fundamental multi-stage flow physics, thereby identifying and quantifying the key unsteady aerodynamic parameters relevant to aero-thermodynamic distortion induced responses of blading. The wakes from upstream blade and vane rows and the upstream and downstream potential interactions are the primary source of the unsteady aerodynamics on the downstream blade rows. Hence, it is necessary to experimentally model the basic unsteady aerodynamic phenomena inherent in this time-variant interaction, including the incidence angle, the velocity and pressure variations, the aerodynamic forcing function waveforms, the reduced frequency, and the blade row interactions.

These fundamental phenomena are all simulated in the Purdue University three-stage axial flow research compressor, Figure 1. The compressor is driven by a 15 HP DC electric motor over a speed range of 300 to 3000 RPM. The inlet section is located aft of the drive motor. In the exit of this section are 38 variable geometry guide vanes which direct the flow into the test section. Three identical compressor stages are mounted in the test section, which has an annulus with constant hub (0.300 m) and tip (0.420 m) diameters. The exit flow from the test section is directed through a series of flow straighteners into a venturi meter which enables the mass flow rate to be determined. To throttle the compressor, an adjustable plate is located at the exit of the diffuser of the venturi.

Each of the three identical compressor stages consists of 43 rotor blades and 41 stator vanes. Hence, the interblade phase angle for these experiments is 17.56° . These free vortex design airfoils have a British C4 section profile, a chord of 30 mm, and a maximum thickness-to-chord ratio of 0.10. The overall airfoil and compressor characteristics are presented in Table 1.

Conventional steady-state instrumentation is used to determine the flow properties in the compressor. The inlet temperature is measured by four equally spaced thermocouples at the inlet of the compressor. Casing static taps, equally spaced circumferentially, allow the measurement of the static pressure between each blade row. Traversing gear instrument stations provided between each blade row are used to measure the mean flow

	Rotor	Stator
Type of Airfoil	C4	C4
Number of Blades	43	41
Chord, C(mm)	30	30
Solidity, C/S	1.14	1.09
Camber	27.95	27.70
Aspect Ratio	2.0	2.0
Thickness/Chord (%)	10	10
Flow Rate (kg/second)	2.66	
Rotor-Stator Axial Spacing (mm)	22.2	
Design Axial Velocity (meters/sec)	32.0	
Rotational Speed (RPM)	3000	
Number of Stages	3	
Stage Pressure Ratio	1.003	
Inlet Tip Diameter (mm)	420	
Hub/Tip Radius Ratio	0.714	
Stage Efficiency (%)	85	

TABLE I. AIRFOIL MEAN SECTION CHARACTERISTICS AND
COMPRESSOR DESIGN POINT CONDITIONS

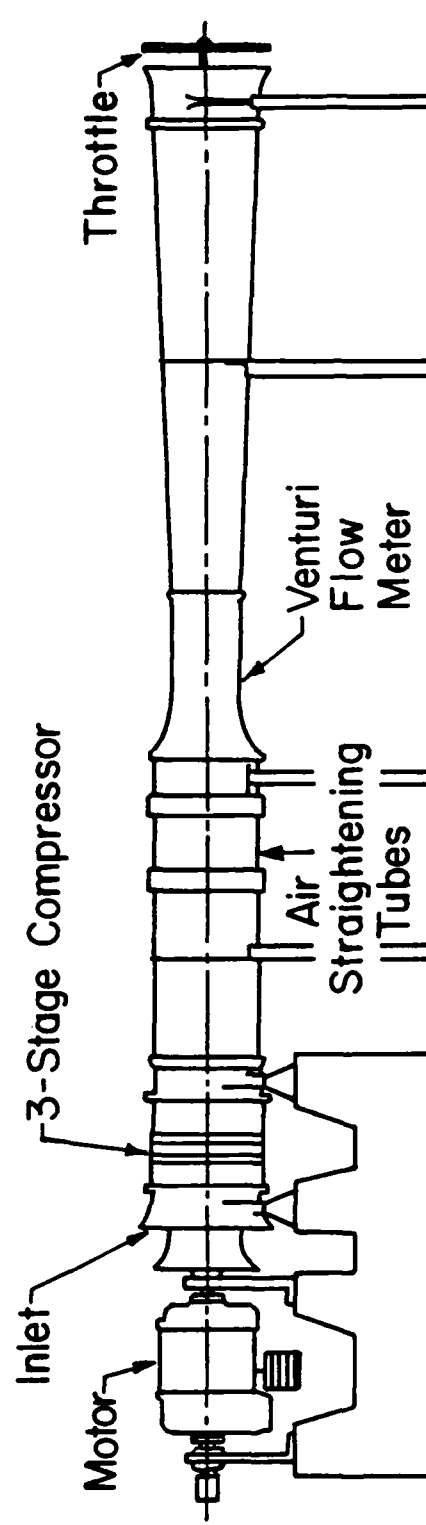


Figure 1. Three-stage axial flow research compressor

incidence angle. A thermocouple and Kiel probe located downstream are used to measure the compressor exit temperature and total pressure, respectively. The mass flow is measured with the calibrated venturi meter located downstream of the compressor test section. A shaft mounted 60 tooth gear and a magnetic pickup provide the rotor speed.

IV. PROGRAM STATUS AND RESULTS

The specific accomplishments during this reporting period are outlined below, with a more detailed discussion following.

Overview

EXPERIMENTAL TECHNIQUES

- * Completion of the development and implementation of the overall steady and unsteady data acquisition and analysis systems
- * Implementation of the cross hot-wire system into the overall research compressor instrumentation
- * Instrumentation of the rotors and additional stators with new dynamic pressure transducers which offer significantly increased sensitivity and reduced size

VANE ROW EXPERIMENTS

- * Implementation of the techniques to measure the unsteady aerodynamic forcing functions to the stator vanes
- * Completion of preparations for the potential interaction experiments
- * Completion of the initial first stage vane row unsteady aerodynamic experiments

- * Initiation of the multi-stage interaction experiments on the vane rows
- * Analysis of the initial multi-stage vane row unsteady aerodynamic data

ROTOR BLADE EXPERIMENTS

- * Continuation of preparations for the rotor experiments, including the design and start of fabrication of the signal conditioning to be used in the rotating frame of reference

FORCED RESPONSE MODELING

- * Formulation of the viscous flow unsteady aerodynamic model

Initial Multi-Stage Vane Row Experiments

Data Acquisition and Analysis

The steady-state aerodynamic loading of the vane rows is determined by instrumenting a pair of stator vanes with chordwise distributions of surface static pressure taps. Only one pair of vanes is instrumented as the three vane rows are identical and interchangeable.

The unsteady aerodynamic data of fundamental interest in these initial experiments are: (1) the unsteady aerodynamic forcing function to the stators, i.e., the wakes from the upstream blade rows; (2) the resulting chordwise distributions of the complex time-variant pressure difference across the chordline of the stator vane rows.

The aerodynamic forcing function is measured with a cross-wire probe calibrated and linearized to 45 m/s and $\pm 35^\circ$ angular variation. The mean absolute exit flow angle from the rotor is determined by rotating the cross-wire probe until a zero voltage difference is obtained between the two linearized hot-wire signals. This mean angle is then used as a reference for calculating the instantaneous absolute and relative flow angles. The output from each channel is corrected for tangential cooling effects and the individual fluctuating velocity components parallel and normal to the mean flow angle, the components of the aerodynamic gust, calculated from the corrected quantities.

These initial airfoil surface dynamic pressure measurements are accomplished with Kulite thin-line design dynamic pressure transducers. As per the steady instrumentation on the stator vanes, only two vanes are instrumented. The suction surface of one vane and the pressure surface of a second are instrumented with these transducers at 14.1, 29.1, 47.4, and 63.7% of the vane chord. To minimize any flow disturbances generated by the transducers, they are embedded in the vanes and connected to the surface by a static pressure tap with the lead wires placed in milled slots and carried out through hollow trunnions.

As schematically depicted in Figure 2, each set of instrumented vanes are located such that a flow passage is instrumented. Also, the cross-wire probe is located axially upstream of the leading edge of the stator row at mid-stator circumferential spacing in a non-instrumented vane passage.

The steady-state compressor performance data acquisition follows the standard evaluation procedure. At the selected corrected speed, the compressor is stabilized for approximately 10 minutes, after which the steady state data acquisition is initiated and controlled by a PDP 11-23 computer. The data are then analyzed, and the corrected mass flow, pressure ratio, corrected speed, and vane surface static pressure distributions determined.

The time-variant data acquisition and analysis technique used is based on a data averaging or signal enhancement concept. The key to such a technique is the ability to sample data at a

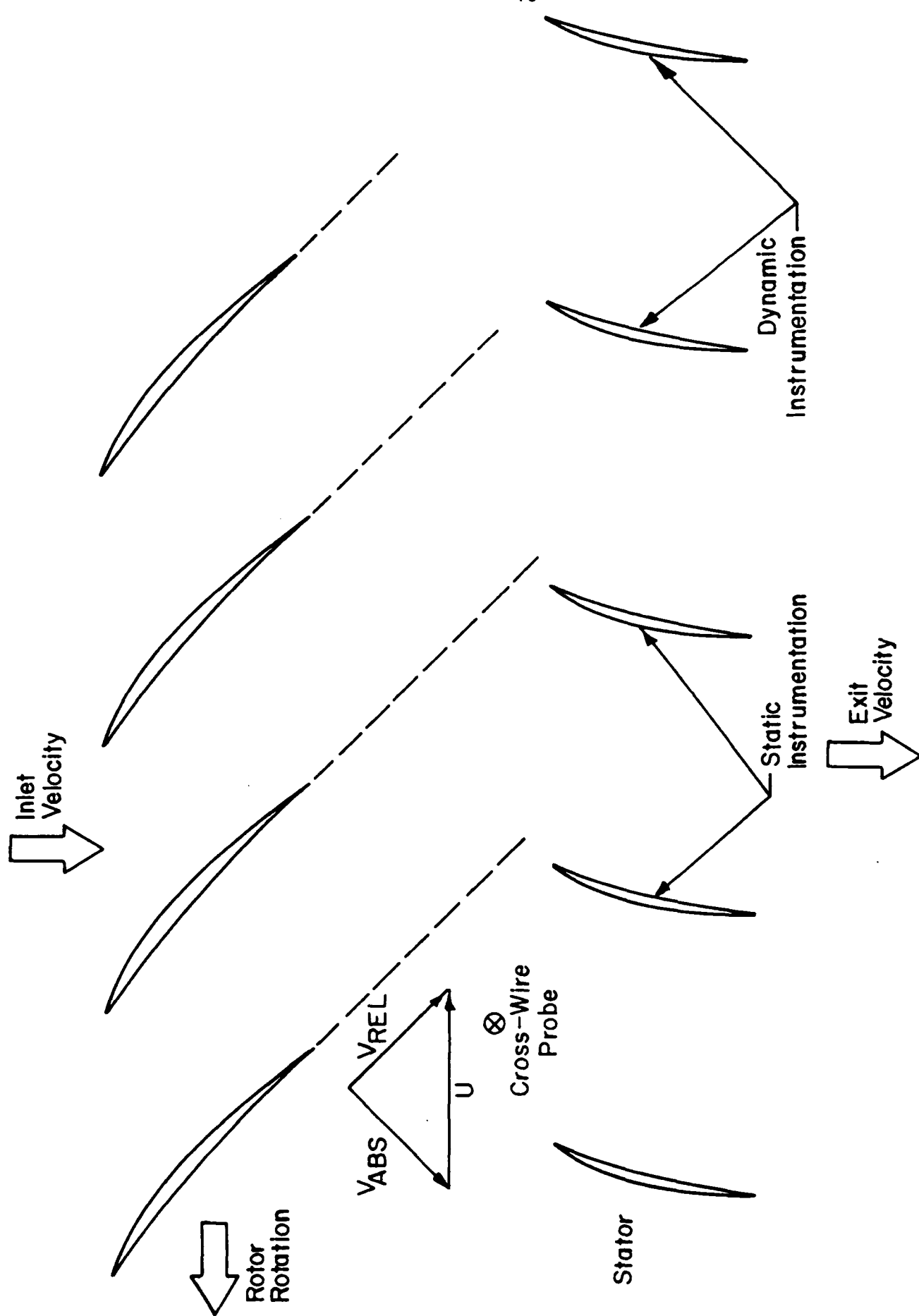


Figure 2. Schematic of flow field and instrumentation

preset time. In this investigation, the data of interest are generated at the blade passing frequency. Hence, an optical encoder, delivering a square wave voltage signal with a duration in the microsecond range, is mounted on the rotor shaft and used as the time or data initiation reference to trigger the A-D multiplexer system. This system is capable of digitizing signals simultaneously at rates to 5 megahertz per channel, storing 2048 data points per channel.

The effect of averaging the time-variant digitized pressure signals from the blade mounted dynamic pressure transducers was considered. Figure 3 displays the time-variant pressure signal from the 14.1% chord pressure surface dynamic pressure transducer for 1 rotor revolution and averaged over 25, 50, 75, and 100 rotor revolutions. As seen, averaging greatly reduces the random fluctuations superimposed on the harmonic pressure signal. Also, these time-variant pressure signals are essentially unchanged when averaged over 75 or more rotor revolutions.

At each steady-state operating point, an averaged time-variant data set, consisting of the two hot-wire and the Kulite dynamic pressure transducer signals digitized at a rate of 200 Khz and averaged over 100 rotor revolutions, are obtained. These rotor revolutions are not consecutive due to the finite time required for the A-D multiplexer system to sample the data and the computer to then read the digitized data.

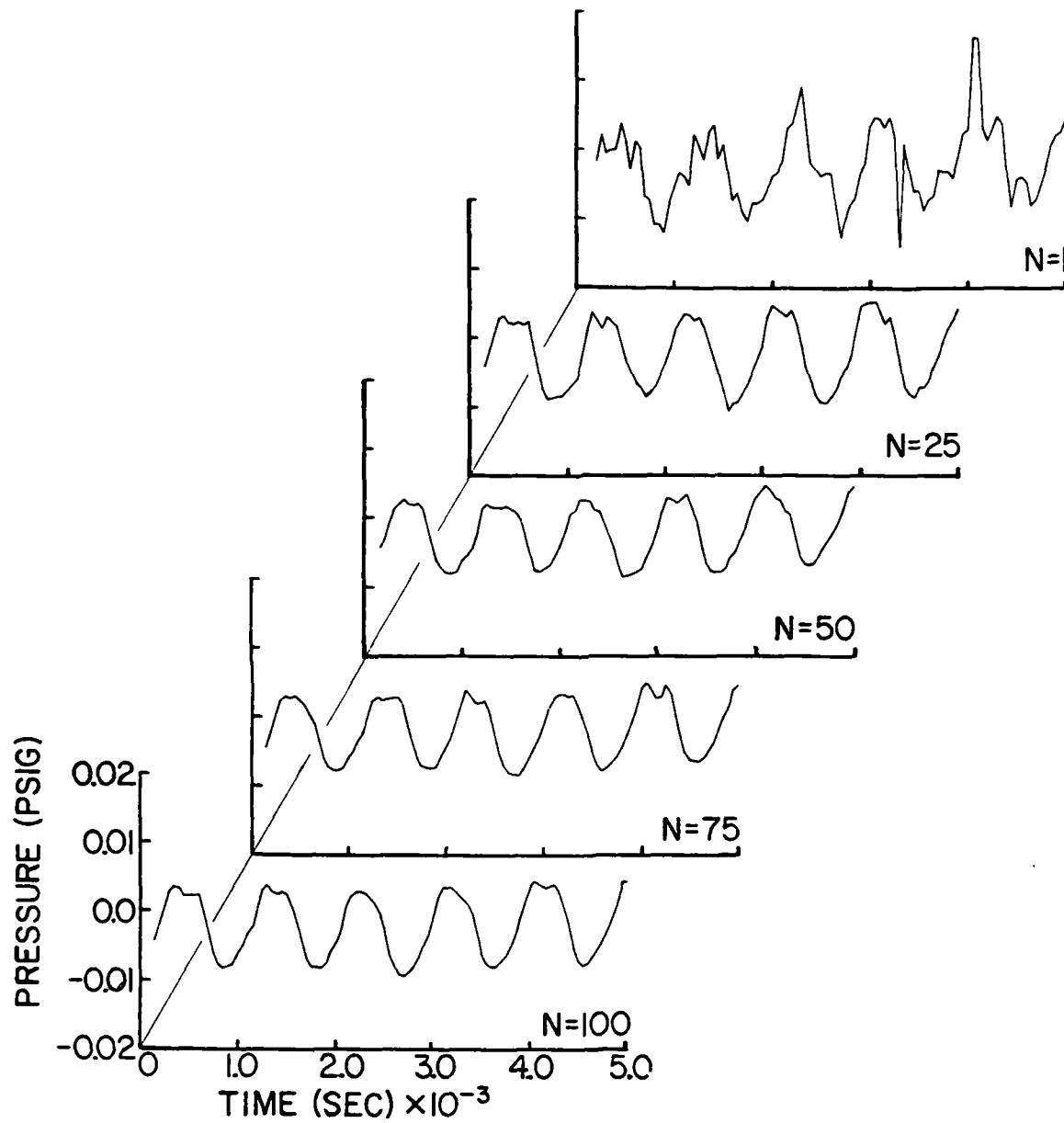


Figure 3. Averaging of unsteady pressure signals

Each of these digitized signals is Fourier decomposed into harmonics by means of an FFT algorithm. Figure 4 shows an example of this decomposition for the 14.1% chord pressure surface transducer signal. As seen, the transducer signal contains a dominant fundamental frequency at the blade passing frequency and much smaller higher harmonics. In addition, the averaged signal exhibits minimal non-harmonic content. From this Fourier decomposition, both the magnitude of each component and its phase lag as referenced to the optical encoder pulse are determined.

From the Fourier analysis performed on the data, the magnitude and phase angle of the first harmonic as referenced to the data initiation pulse is obtained. To then relate the wake generated velocity profiles with the first harmonic surface dynamic pressures on the instrumented vanes, the rotor exit velocity triangles are examined. Figure 5 shows the change in rotor relative exit velocity which occurs as a result of the presence of the blade. A deficit in the velocity in this relative frame creates a change in the absolute velocity vector as indicated. This velocity change is measured with the crossed hot-wires. From this, the instantaneous absolute angle and velocity as well as the magnitude and phase of the perturbation quantities are determined.

As noted previously, the hot-wire probe is positioned upstream of the leading edge of the stator row. To relate the time based events as measured by this hot-wire probe to the unsteady pressures on the vane surfaces, the following

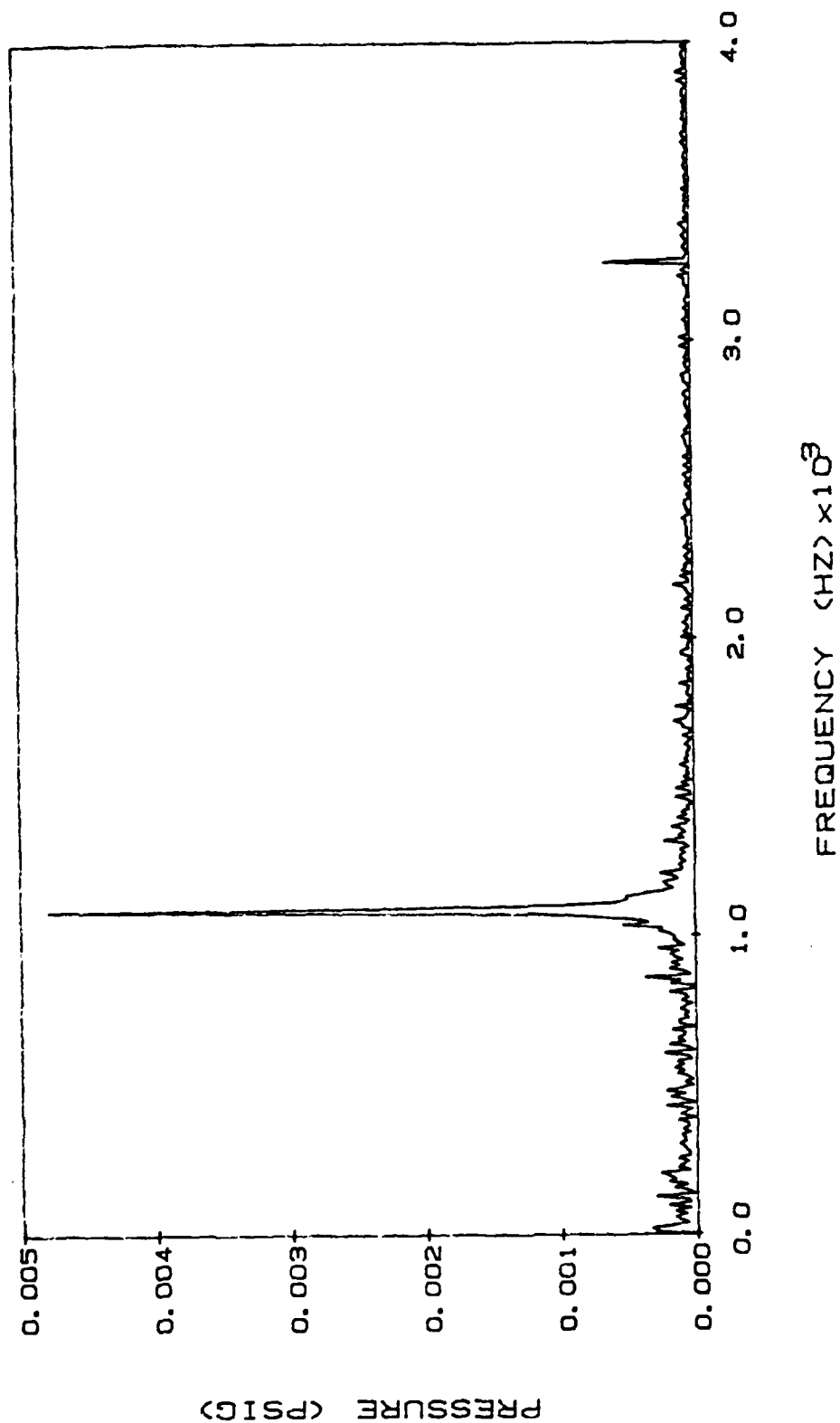


Figure 4. Fourier decomposition of averaged unsteady pressure signal

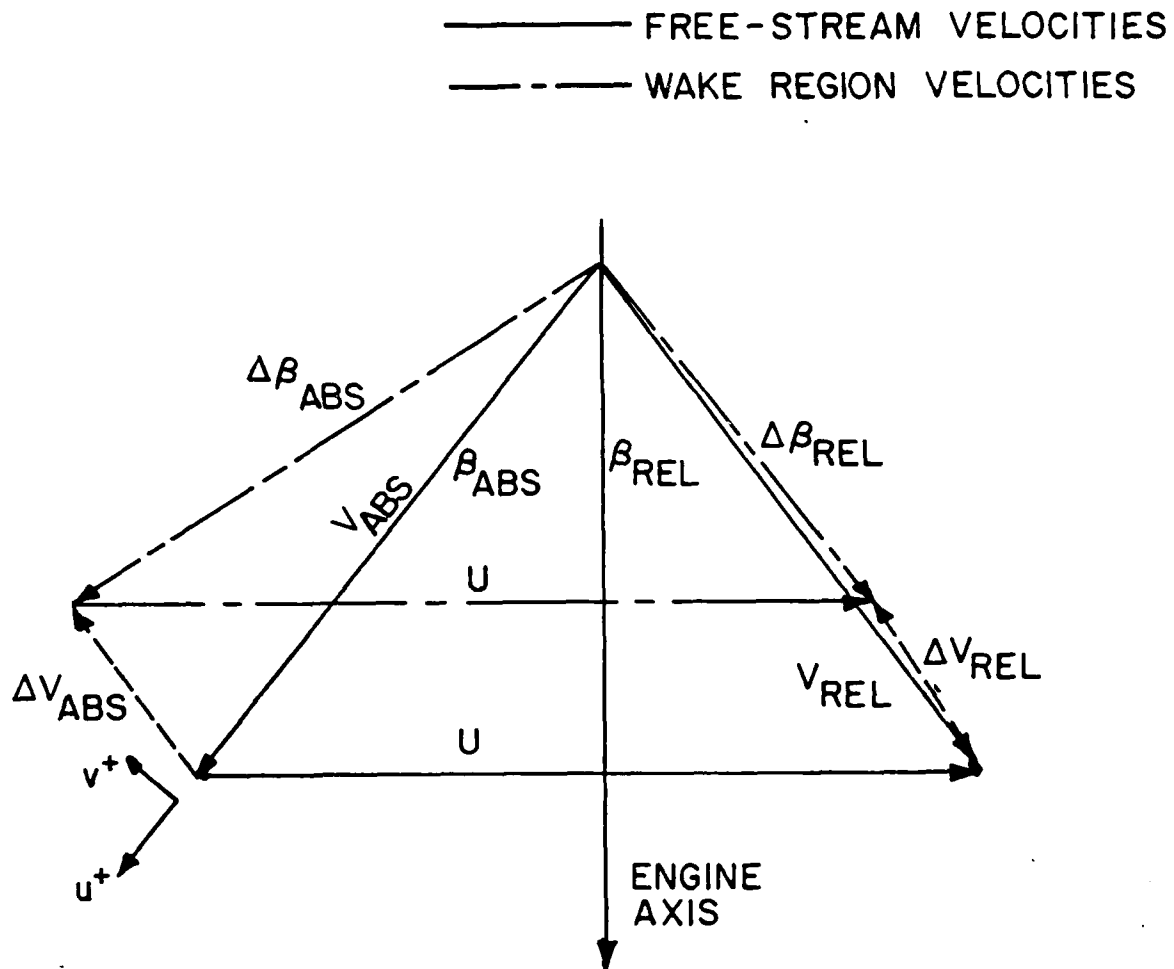


Figure 5. Variation of absolute velocity due to rotor blade wakes

assumptions are made: (1) the wakes are identical at the hot-wire and the stator leading edge planes; (2) the wakes are fixed in the relative frame. A schematic of the rotor wakes, the instrumented vanes, and the hot-wire probe was presented in Figure 2. The rotor blade spacing, the vane spacing, the length of the hot-wire probe, and the axial spacing between the vane leading edge plane and the probe holder centerline are known quantities. At a steady operating point, the hot-wire data is analyzed to determine the absolute flow angle and the rotor exit relative flow angle. Using the above two assumptions, the wake is located relative to the hot-wires and the leading edges of the instrumented vane suction and pressure surfaces. From this, the times at which the wake is present at various locations is determined. The increment times between occurrences at the hot-wire and the vane leading edge plane are then related to phase differences between the perturbation velocities and the vane surface.

To simplify the experiment-theory correlation process, the first harmonic data is adjusted in phase such that the transverse perturbation is at zero degrees at the vane suction surface leading edge. From the geometry indicated in Figure 2, the time at which this would occur is calculated and transposed into a phase difference. This difference is then used to adjust the pressure data from the suction surface. A similar operation is performed on the pressure surface data so that the surfaces of the vanes are time related; i.e., time relating the data results in data equivalent to that for a single instrumented vane. Following

this procedure, the first harmonic pressure differences across an equivalent single vane at each transducer location are calculated. The final form of the unsteady pressure data describes the chordwise variation of the first harmonic pressure difference across a stator vane and is presented as an aerodynamic phase lag referenced to a transverse gust at the airfoil leading edge and the dynamic pressure coefficient, $C_p = \Delta p / (\rho v_{axial}^2 \frac{v}{V_{axial}})$.

Results

The objective of this initial series of experiments is the quantitative investigation of the blade row interaction first harmonic gust unsteady aerodynamics. This is accomplished by measuring the aerodynamic forcing functions and the chordwise distributions of the steady pressures and the first harmonic unsteady pressure differences on the first and second stage stator vane rows of a three-stage research compressor over a range of operating and geometric conditions.

The chordwise distributions of the first harmonic of the complex unsteady pressure differences across the vane rows are correlated with predictions obtained from a periodic gust model which considers the inviscid, irrotational, flow of a perfect gas. This model analyzes the uniform subsonic compressible flow past a two-dimensional flat plate airfoil cascade, with small unsteady normal velocity perturbations superimposed and convected downstream. The parameters include the cascade solidity and

stagger angle, the interblade phase angle, the inlet Mach number, and the reduced frequency.

The first stage vane steady and first harmonic unsteady data at incidence angles of -9.2° , -10.3° , and -14.5° , are presented in Figures 6 and 7, respectively. No evidence of flow separation is evident in the vane surface static pressure distributions, with the steady aerodynamic loading a function of the incidence angle, as expected. However, the first harmonic unsteady data, Figure 7, are nearly independent of the incidence angle and the steady loading over this range of operating conditions. The differences between the zero incidence flat plate predictions and these unsteady data are attributed to the camber of the airfoil and incidence angle effects.

The second stage steady loading distributions and the correlation of the first and second stage unsteady data for this same range of incidence angles and reduced frequency values are presented in Figures 8 and 9, respectively. The chordwise static pressure distributions on the vane surfaces are similar for both stages, with the steady aerodynamic loading a function of the incidence angle and no evidence of flow separation. The second stage unsteady data exhibit the same overall trends as that of the first stage. However, unlike the first stage results, these second stage unsteady data, particularly the dynamic pressure coefficient, are a function of the incidence angle and, thus, the steady-state loading.

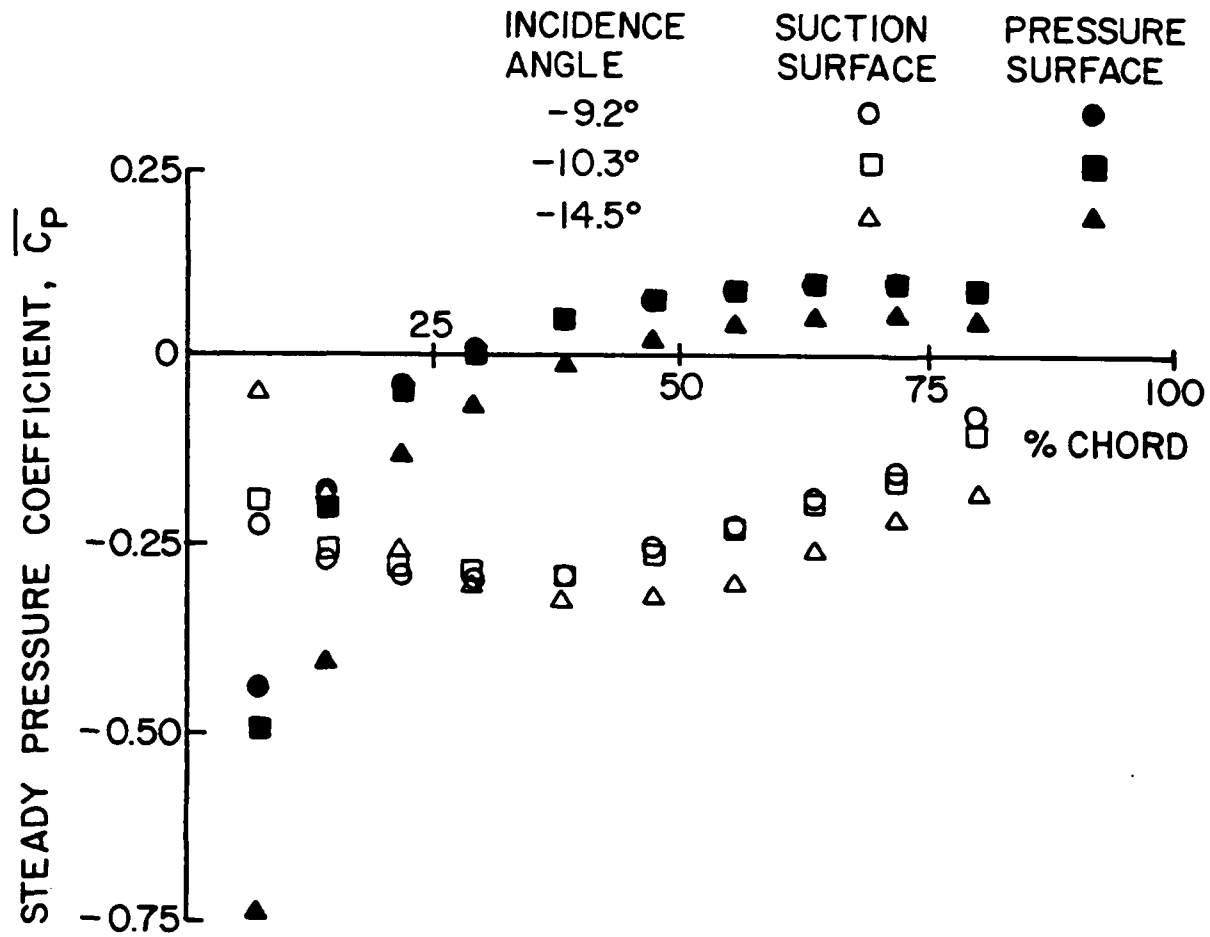


Figure 6. First stage vane static pressure coefficient distribution

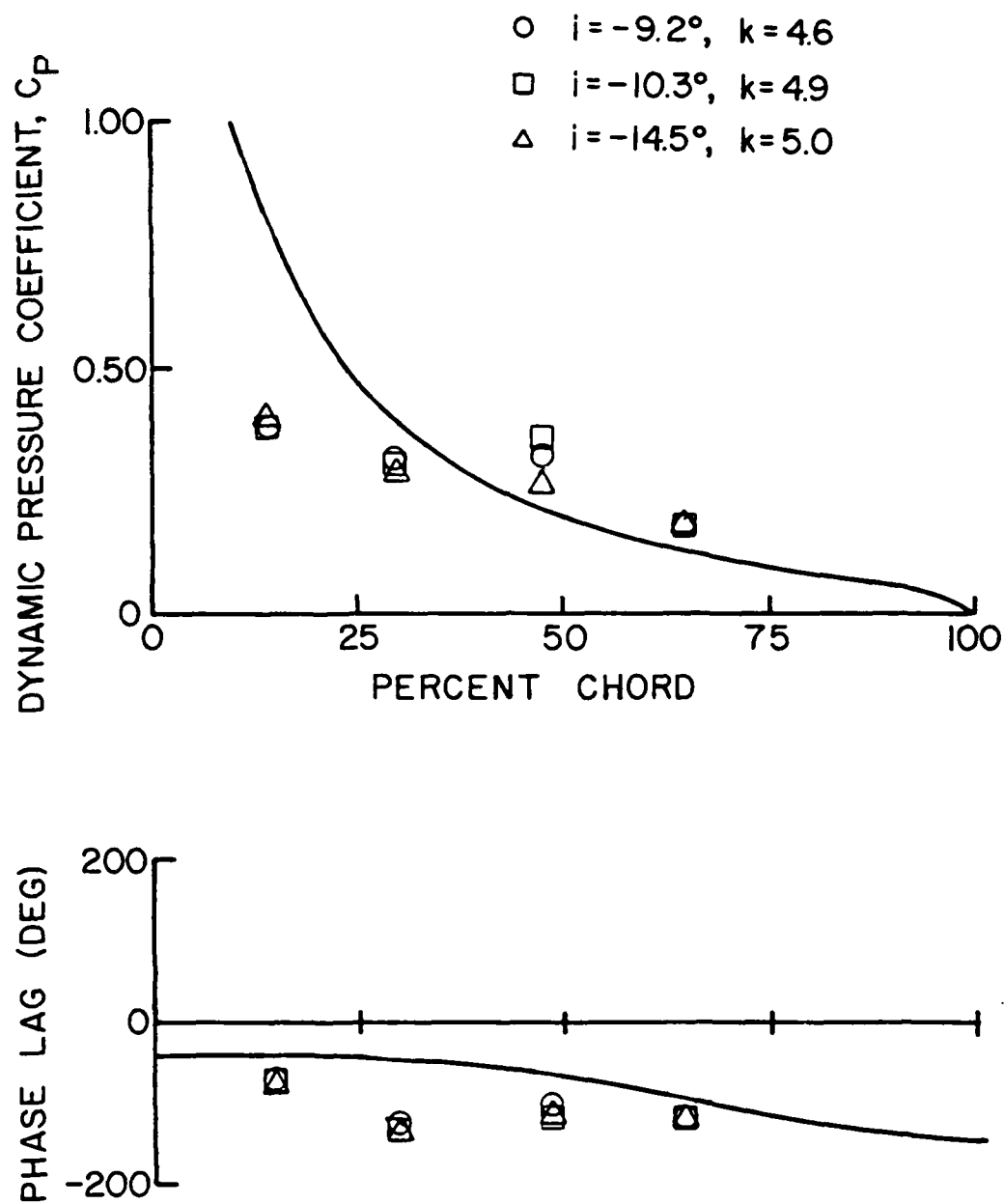


Figure 7. First harmonic unsteady data correlation for first stage vane

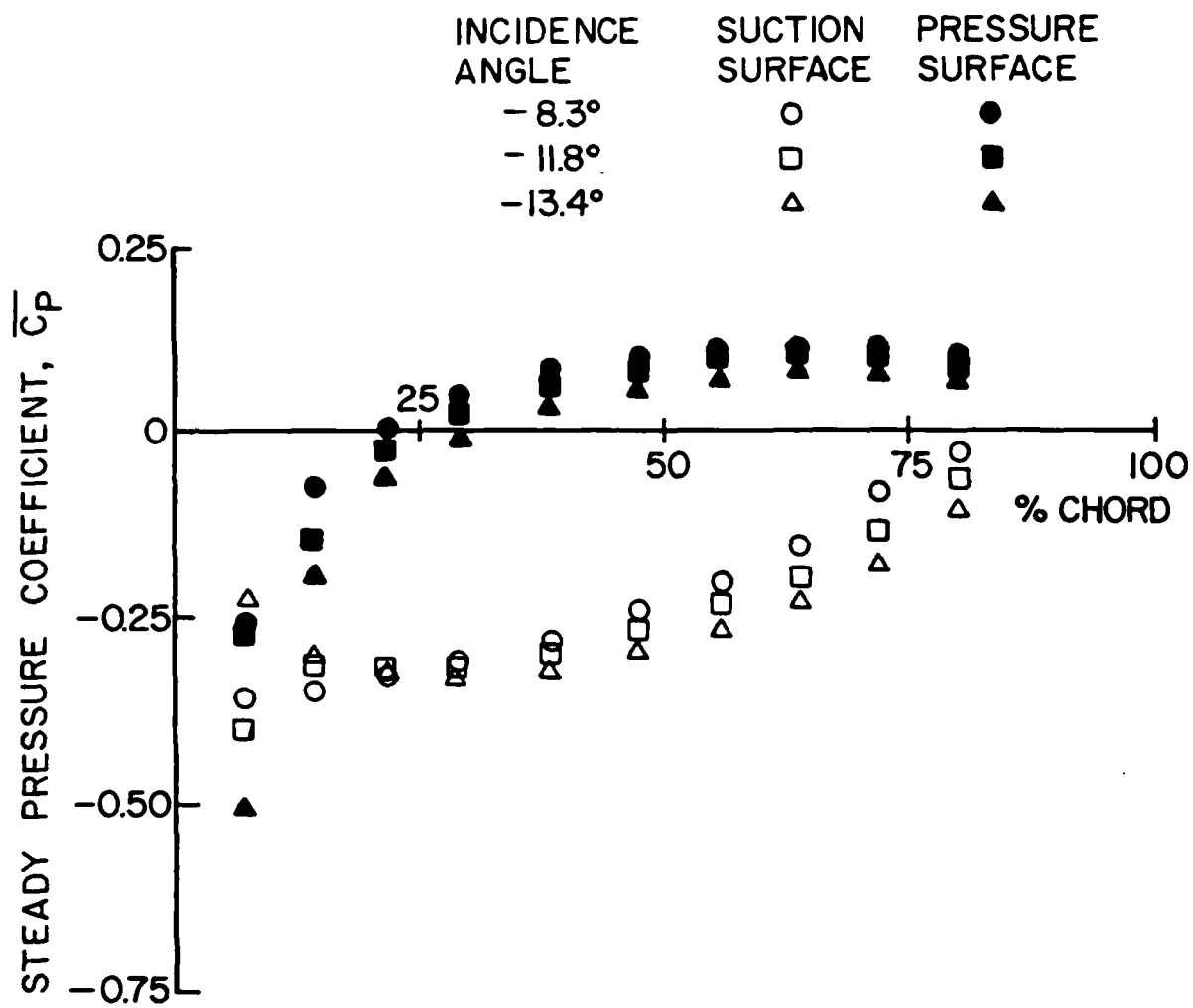


Figure 8. Second stage vane static pressure coefficient distribution

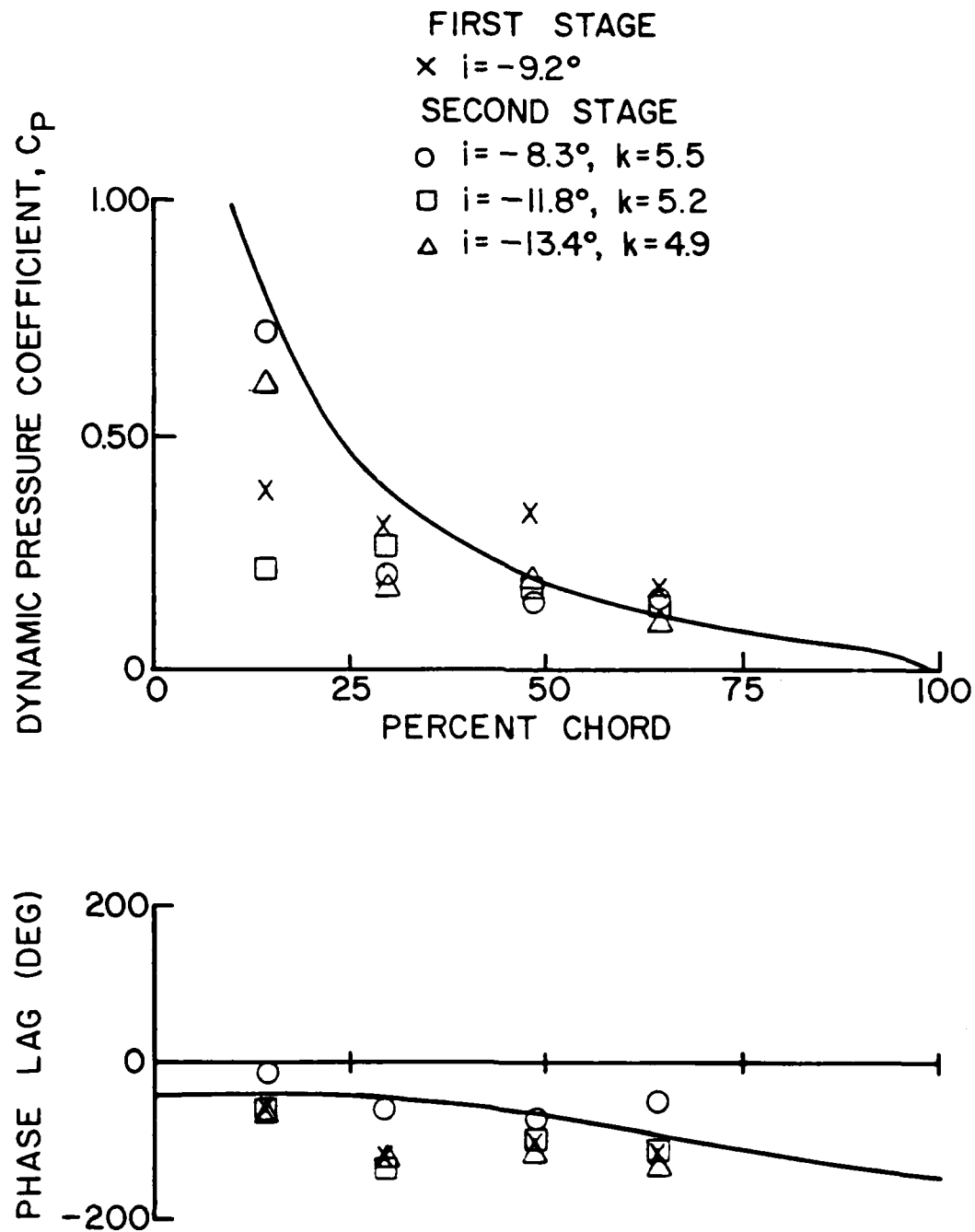


Figure 9. First harmonic unsteady data correlation for second stage vane

To understand this difference in the effect of incidence angle on the first and second stage unsteady data, it is necessary to consider the aerodynamic forcing functions for the unsteady pressure data, i.e., the upstream wakes impinging on the downstream stator vanes. Figure 10 presents the wake normal perturbation velocity waveforms which are the forcing function to the first stage vane row data of Figure 7. As seen, these waveforms are nearly identical to one another. The corresponding second stage vane row inlet normal perturbation velocity waveforms are presented in Figure 11. These waveforms differ significantly from one another and also from the first stage wake waveforms. This variation in waveform of the second stage forcing function with steady operating point is a multi-stage blade row interaction effect, with the second stage rotor wake being modulated by the wakes from the upstream first stage rotor and stator airfoils.

The research compressor used in this study offers the ability to investigate this multi-stage unsteady blade row interaction effect. This is because the first stage stator vanes can be indexed circumferentially relative to the second stage vane row. Thus, this multi-stage unsteady blade row interaction is investigated at a fixed steady-state operating point by indexing the first stage stator row relative to the second stage vane row, as schematically depicted in Figure 12. Specifically, with the first stage stators indexed 0, 25, 50, and 75%, relative to the

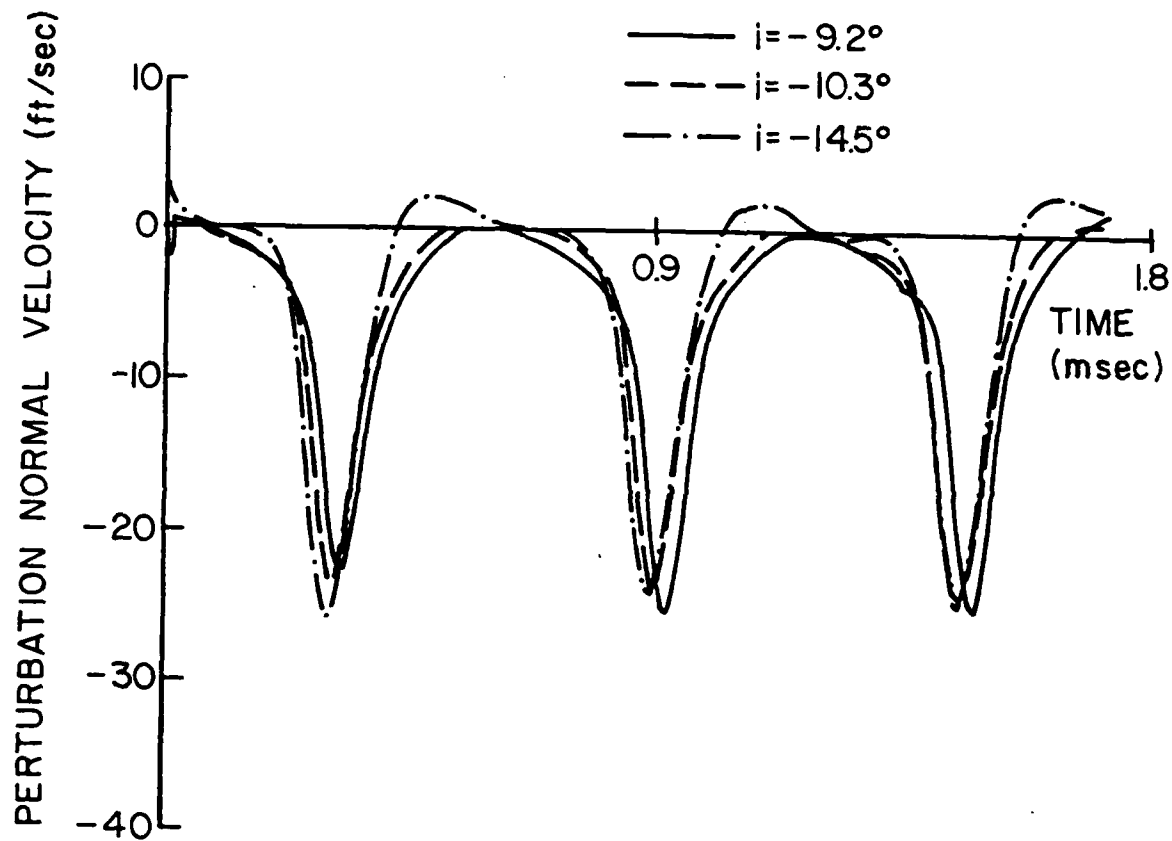


Figure 10. First stage vane aerodynamic forcing function waveform

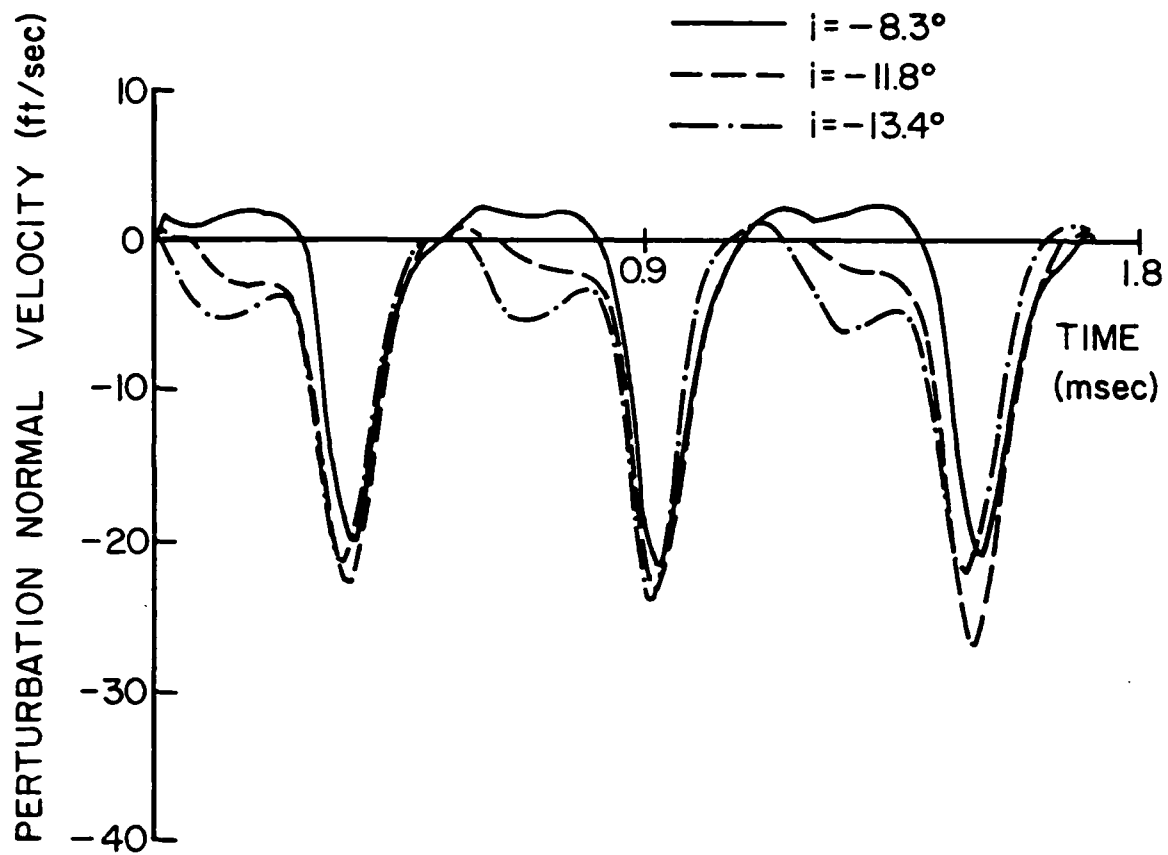


Figure 11. Second stage vane aerodynamic forcing function waveform

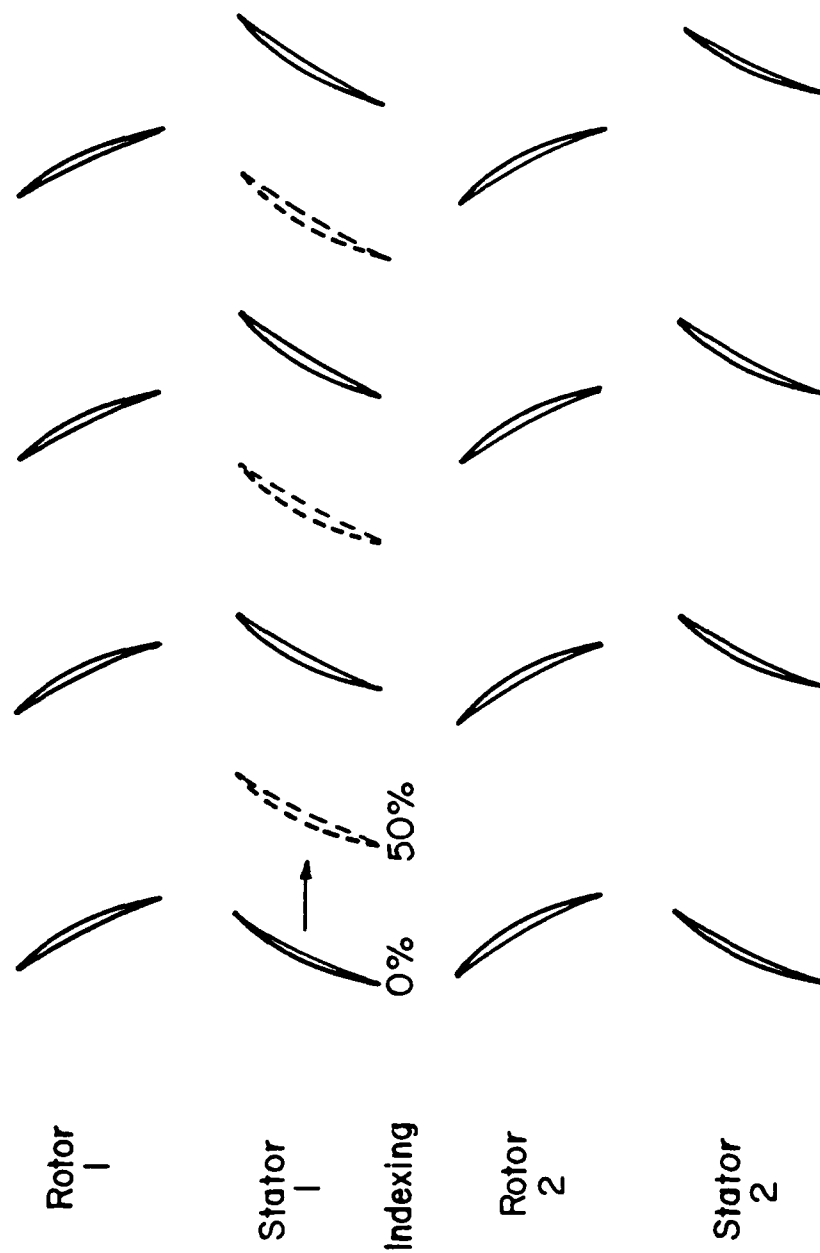


Figure 12. Schematic of circumferential indexing of first stage stator row

second stage vane row, complete steady and unsteady second stage vane row data sets are obtained.

The circumferential indexing of the first stage stator vanes has no effect on the second stage vane steady-state loading distributions, Figure 13. However, it does have a significant effect on the waveform of the aerodynamic forcing function to the second stage vanes. In particular, the relative stator positioning results in the modulation of the waveform of the second stage rotor wakes, as seen in Figure 14. This waveform modulation of the primary forcing function to the second stage vane row affects the complex unsteady pressure distributions on this vane row, Figures 15 and 16, with the larger effect found at the lower steady loading.

These variations of the unsteady data with forcing function waveform cannot be predicted by harmonic gust models. This is because the forcing function waveforms and the resulting unsteady pressure distributions have been Fourier decomposed, with the first harmonics of the unsteady data presented. Thus, all of these first harmonic unsteady data are correlated with the same prediction curve, as indicated in Figures 15 and 16, i.e., the predictions from these harmonic gust models are identical for all of the forcing function waveforms.

Conclusions

This initial series of experiments has demonstrated a significant effect of multi-stage blade row interactions on the

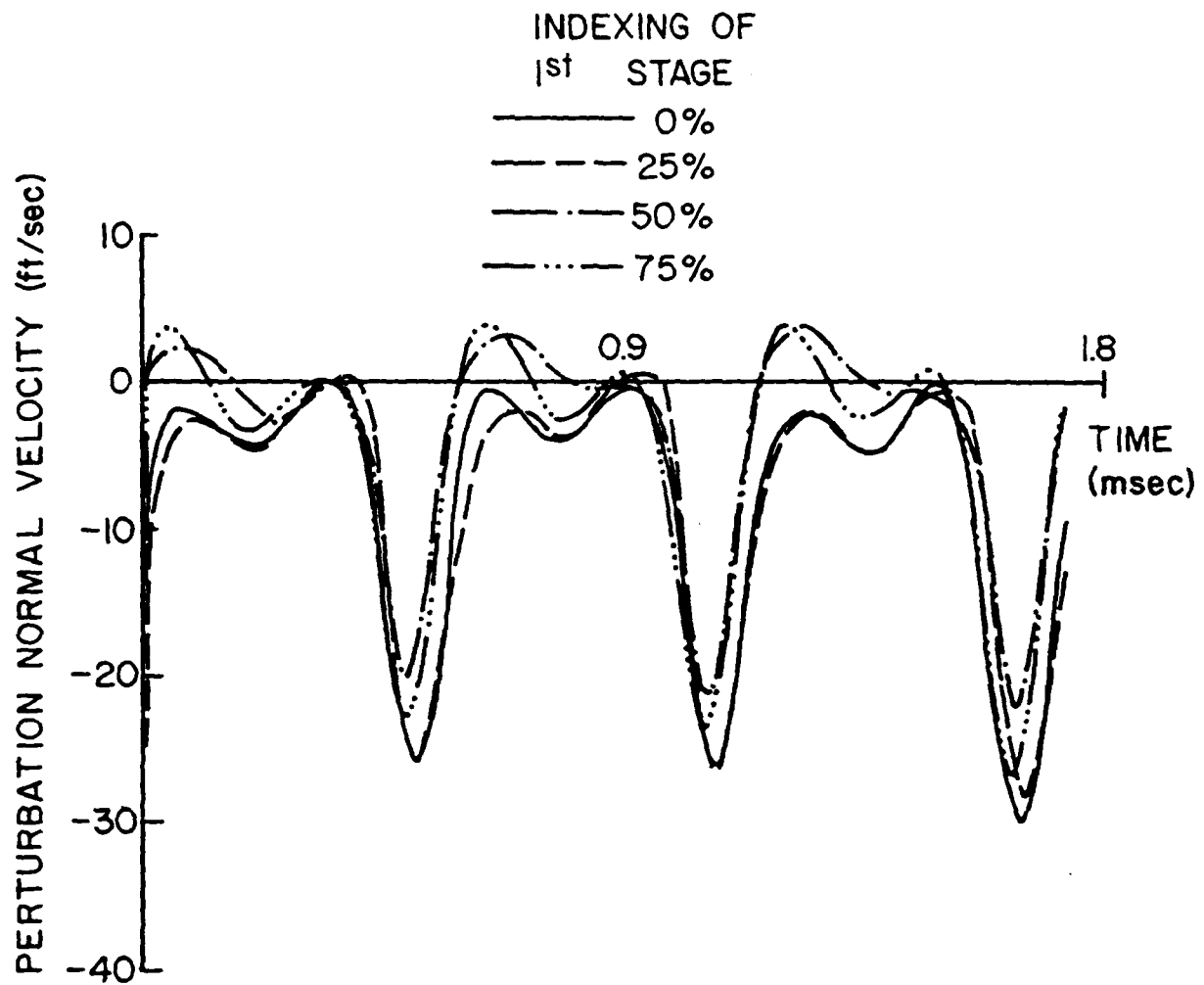


Figure 14. Effect of first stage stator indexing on second stage vane forcing function waveform

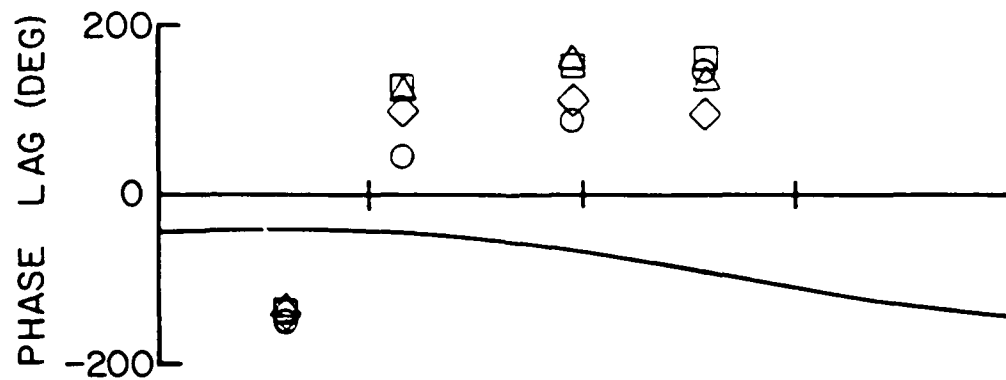
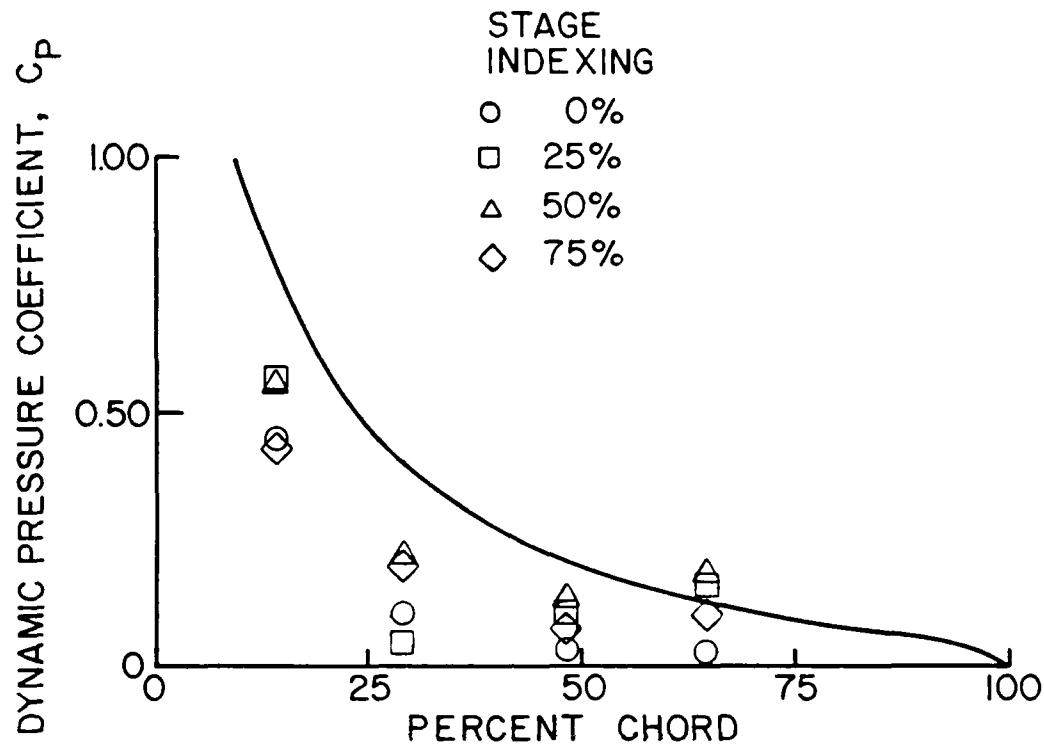


Figure 15. Effect of first stage vane indexing on second stage vane unsteady data at -10° of incidence

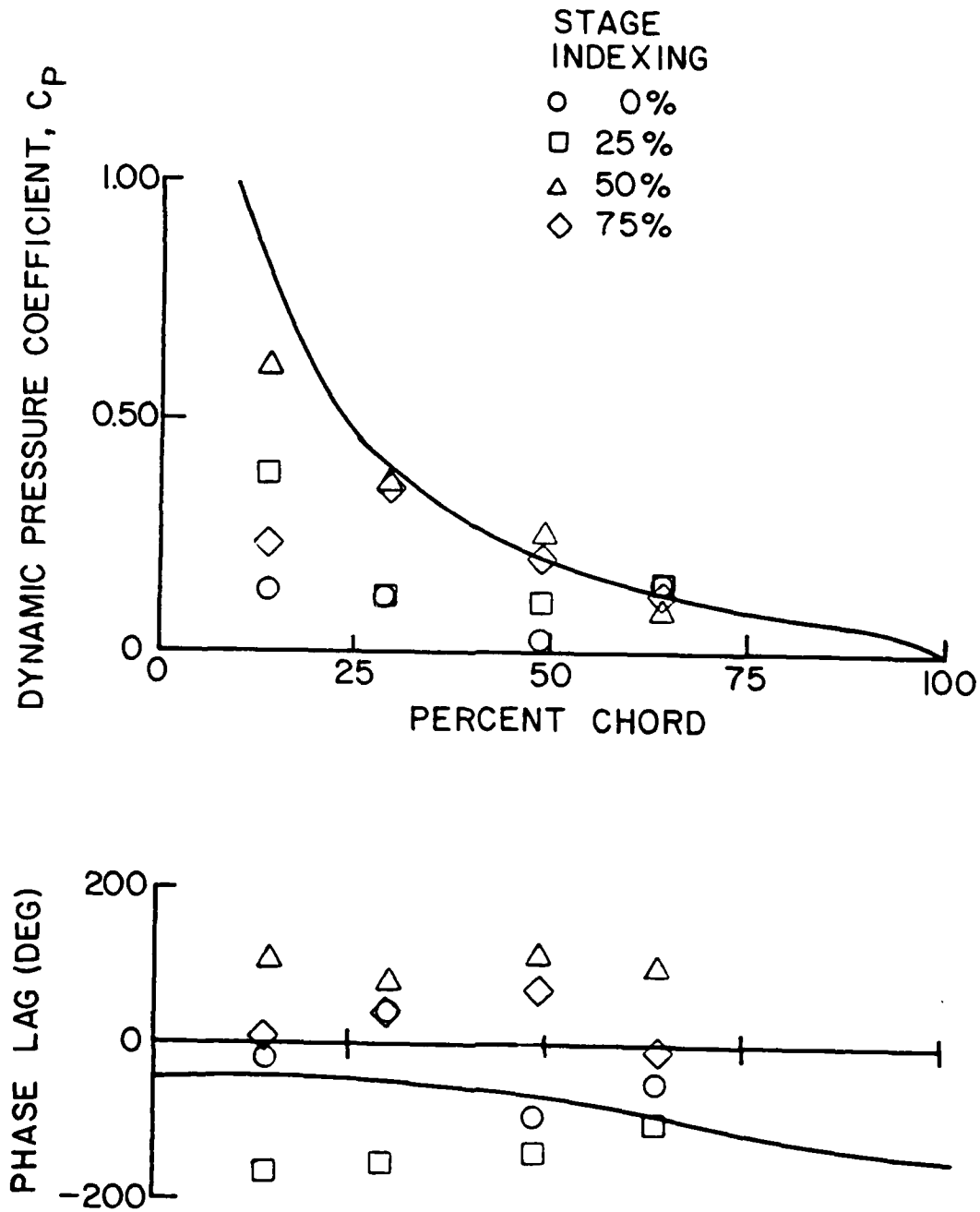


Figure 16. Effect of first stage vane indexing on second stage vane unsteady data at -16° of incidence

unsteady aerodynamics of downstream blade rows. In particular, the first stage blade rows modulate the waveform of the aerodynamic forcing function to the second stage vane row. This has no effect on the steady loading of the second stage vanes, but does have a significant effect on the resulting complex unsteady chordwise pressure difference distributions. Thus, the complex unsteady aerodynamic loading on downstream blade rows is directly related to the forcing function to that blade row, with this forcing function significantly affected by multi-stage blade row interaction phenomena. These results have an implication towards the modeling of unsteady aerodynamic blade row interaction phenomena. Namely, the variations of the second stage unsteady data with forcing function waveform cannot be predicted by harmonic gust models, i.e. the predictions from these gust models would be identical for all of the forcing function waveforms.

Rotor Studies

The development of the dynamic instrumentation and calibration procedures for the first stage rotor blade studies has been continued. Modifications to the rotor shaft to route lead wires to the slip ring assembly have been completed and a slip ring assembly acquired. Also, the design of the rotating signal conditioning system has been completed and fabrication initiated. In addition, dynamic pressure transducers are now being installed on the rotor blades. These are a new type of transducer which offer significantly increased sensitivity and reduced size.

Modeling

The formulation of the viscous flow unsteady aerodynamic model has been completed and development of the computer code initiated.

V. PUBLICATIONS AND THESES

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